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Modelling small-scale trigenerative advanced adiabatic compressed air energy storage for building application

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Abstract

The energy storage technology offers an energy balance by saving energy production for periods of higher customer demand. The present study concerns the development of a numerical model to simulate the trigeneration micro advanced adiabatic compressed air energy storage system (AA-CAES) coupled to building model and energy grids. Different design parameters are grouped and therefore an ideal prototype is proposed based on a global numerical sizing tool which in turn based on solving energy balance and heat transfer equations for each components (photovoltaic panels, wind turbines, compressor, turbine, reservoir). This study proposed two modes of operation depending on the electrical grid connection to the building (Autonomous and connected mode operation). From energy coverage point of view, it was noted that the connected mode operation scored more advantage points than the autonomous mode operation in most of the geographical scenarios. In best energetic case configuration the electrical coverage ratio scored 25.52 %, the hot coverage ratio was equal to 20 % and the cold coverage ratio scored 8 %. The trigeneration system efficiency was noticed to be a compromise between electrical coverage ratio, hot coverage ratio and cold coverage ratio.

Nomenclature

c	specific heat, $\text{J.kg}^{-1}.\text{K}^{-1}$	in	input
E	energy, Wh	j	time step
H	enthalpy, J	out	output
h	specific enthalpy, J.kg^{-1}	PV	photovoltaic
K	global thermal coefficient, $\text{W.m}^{-2}.\text{K}^{-1}$	p	constant pressure
\dot{m}	mass flow rate, kg.s^{-1}	RE	renewable energy
m	mass, kg	res	reservoir
Q	heat transfer, J	ret	return
q	heat transfer rate, J.s^{-1}	ST	storage
t	time, s	t	turbine
T	temperature, K	v	constant volume
u	specific internal energy, J.kg^{-1}	w	wind
w	specific work, J.kg^{-1}		

Subscripts

amb	ambient
c	compressor
co	cold
EBD	electrical building demand
GR	grid
HE	heat exchanger
ho	hot
i	stage number

Superscript

w	water
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Greek letters

Δ and δ	delta
γ	heat capacity ratio
α	boolean coefficient
β	compression/ expansion ratio
θ	exergy
ϵ	efficiency

Abbreviation

$AA-CAES$	advanced adiabatic compressed air energy storage	Nc	number of compression stages
$CAES$	compressed air energy storage	Nt	number of expansion stages
$C-CAES$	classical compressed air energy storage	NTU	number of Transfer Units
CCR	cold coverage ratio	PV	photovoltaic
CR	cold ratio	RE	renewable energy
EBD	electrical building demand	RTE	round trip efficiency
ECR	electrical coverage ratio	SE	system efficiency
ELM	electrical load management	SP	System parameter
ESE	electrical system efficiency	$T-CAES$	Trigeneration compressed air energy storage
$ETSE$	Exergy trigeneration CAES system efficiency		
HCR	hot coverage ratio	TCR	total coverage ratio
HE	heat exchanger	TES	thermal energy storage
HR	hot recovered	TSE	Trigeneration system efficiency
$I-CAES$	isothermal compressed air energy storage		

1. Introduction

1.1. World energy overview

A report published by the international energy agency (IEA) states that the global energy demand grew by 2.3 % in 2018, twice as fast as the average rate over the last decade, which led to 1.7 % growth in CO₂ emissions [1]. The non-renewable energies are the primary sources of greenhouse gas emissions which make the planet warmer and therefore forcing the climate to change [2]. These consequences have driven many countries to draft energy transition laws in order to strengthen the energy independence, reduce greenhouse gas emission and accelerate green growth. France, for example, sets many ambitious goals in the energy transition law published in 2015: Bring the share of renewable energies to more than 30 % of the final energy consumption in 2030 and to reduce the share of nuclear power in electricity production to 50 % by 2050 [3].

Renewable energies (R.E.) have become the resources of choice in order to ensure clean energy and reduce greenhouse gas emissions. However, these clean resources are intermittent and depend on the weather conditions. Energy storage technology can be a solution for the energy fluctuating issues and thus stabilizing the grid by allowing excess energy production to be saved for periods of higher customer demand [4,5]. These days, world electrical energy demand is majorly answered by the use of coal, natural gas, nuclear, oil and renewables. The renewable electricity generation scored 25.6 % in 2018 where hydropower-hydraulic storage technology (STEP) presented the important part (75 %). World energy storage deployment reached a record level in 2018 nearly doubling from 2017 to reach over 3 GW [2]. Many major obstacles like installation cost, technical, social, natural and geographical limit the development of the renewable energy technology. For instance, hydropower presents several environmental side effects by blocking, diverting or changing the natural course of river systems and therefore an important migration route for fish. In addition, damming rivers also often reduces water and sediment flow to dangerous levels which impacts downstream wildlife populations. Social-cultural barriers vary from region to another where lack of knowledge and awareness of renewable energy technologies can be challenging for their development. This is not the case in France where according to a survey published in December 2019 by the agency of ecological transition (ADEME), the French people selected the solar energy among other renewable resources as a priority to be more developed [6]. Based on the green energy objectives fixed by

the European Union [7], the different renewable energy barriers should be treated and solved, and therefore the energy storage technology is necessary at that point to boost the development of the renewable technologies at different levels.

1.2. Energy storage technologies

In the current context of the development of renewable energies, energy storage improves energy efficiency and promotes the integration of intermittent renewable energies [5]. It also brings security and flexibility to energy networks. Energy storage involves both heat and electricity. It consists of accumulating energy for later use in a place that may be the same or different from the place of production. Note that the storage allowing to shift the use in time without shifting it in space is called stationary storage and in turn that aimed at mobile applications is called on-board or portable storage [5]. The deployment of low environmental impact storage systems can help to lower the cost of imported electricity necessary to answer the high electrical energy demand and significantly reduce the CO₂ emissions generated by the use of thermal power plants and the dependence on fossil resources. The “French Alternative Energies and Atomic Energy Commission” (CEA) [5] and Luo et al. [8] detailed different energy storage technologies that provide flexibility and enhance the reliability of energy systems (Flywheel, batteries, thermal storage, supercapacitors, hydrogen storage and compressed air energy storage). Each technology depending on its application presents several technical and economic reasons that limit certain of its advantages [9]. Electrical storage that aims to respond to four main issues: recovering excess energy production, supplying energy to compensate the lack of energy due to the intermittent nature of the energy supply especially during high energy demand and supplying energy in the case of an electrical system failure or poor local network quality. Heat storage is primarily intended for heating and cooling buildings, a single-family house in a neighborhood or in a village. Electricity is a very convenient vector for transporting energy but difficult to store in its own form. It is therefore generally transformed to be stored in another form: mechanical energy (potential mechanical [hydraulic storage, compressed air storage], kinetic mechanics [flywheel]), thermal or chemical energy. On the contrary, thermal energy (sensible heat storage, latent heat storage) is usually stored in its original form (heat). Figure 1 reveals the different energy storage technologies showing their applications based on output power range (x-axis) and discharge time (y-axis) where it can be noticed that pumped storage hydroelectricity (red rectangle) presents the highest output power (1 GW) for the longest discharge time (Hours-days).

Batteries (ocean rectangle) can operate for output power between few kilo-watt till hundreds of kilo-watt and for discharge time varying from seconds to minutes.

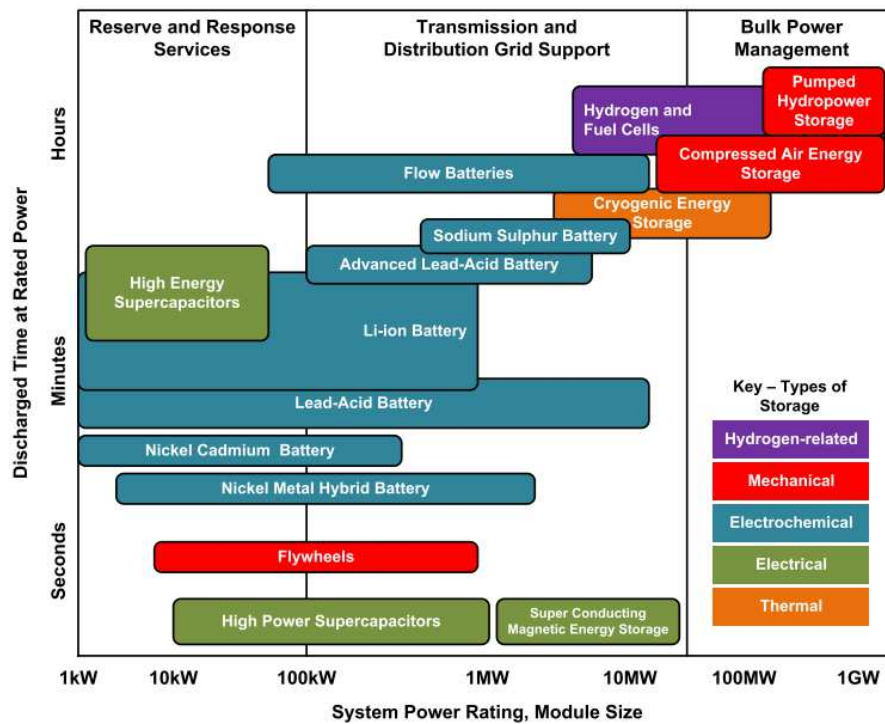


Figure 1: Different storage technologies in function of output power and discharge time [10]

1.3. Compressed air energy storage technology

1.3.1. General concept of compressed air energy storage system

To date, compressed air energy has been used in many fields as an important vector to store different types of energy. Compressed air energy storage system can store large amounts of energy for a period of time in the range of hours making it a possible alternative solution to pumped-storage hydroelectricity. Like the latter storage technology, the large scale CAES system generally requires a particular geographic environment (underground cavities, aquifers, etc.) to store compressed air. The main concept behind the compressed air energy storage is to use the excess electrical energy production to turn a compressor during the storage phase and therefore compress the air at ambient temperature and pressure up to high pressure (50 bar – 100 bar) in order to be stored in a reservoir (underground cavities for example) as shown in Figure 2. During the discharge phase the compressed air (potential energy) is expanded in a turbine which drives a

generator and therefore responds to the lack of electrical energy. The compressed air energy storage (CAES) is usually classified for large scale technology (Megawatt) with hours for responding time.

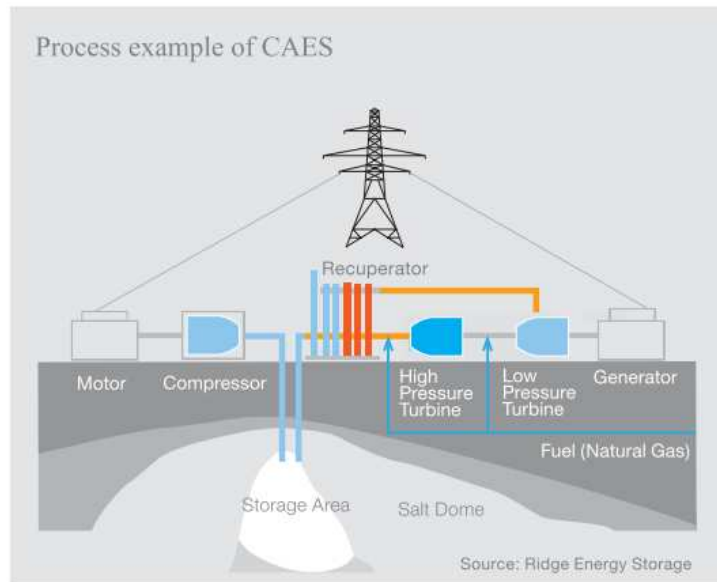


Figure 2: Compressed air energy storage process example [11]

The compressed air energy storage system (CAES) is one of the most promising technologies in the field of smart grid and poly-generation systems in the near future [13]. CAES presents several significant advantages due to its cleanliness, reliability, economic feasibility, long service life and low environmental impact [12]. Venkataramani et al. [4] concluded that the integration of CAES with renewable resources, such as solar and wind, will improve the reliability of these resources through demand side management toward increasing renewable power recovery. In addition, multiple innovative hybrid CAES systems were proposed in the literature [13,14]. Alirahmi et al. [14] scientific work where they proposed a large scale CAES connected to heliostat field and multi-effect thermal vapor compression desalination units. Their hybrid system targeted the energy and water supply where it assures the balance between off-peak and peak demand period. According to CEA, CAES technology presents a competitive investment cost per power and energy unit (€/kW, €/kWh) compared to Li-ion batteries and hydropower technology [5]. Compressed air energy storage can be classified into three main categories:

1. Classical diabatic CAES system (C-CAES)

2. Adiabatic CAES system (A-CAES) / Advanced adiabatic CAES system (AA-CAES)
3. Isothermal CAES system (I-CAES)

The energy storage system studied in this article is based on the second category (A-CAES/AA-CAES) where the compressed air is intercooled during the compression phase and preheated before the expansion phase. The air cooling and preheating processes is achieved by using cold/hot water (or other material or liquid such as oil) reservoirs alongside with heat exchangers that insured the connection with compressors and expanders. Figure 3 shows an example of an AA-CAES configuration proposed by Kim et al. [15] with an electrical input/output system efficiency of 67 %. The latter efficiency was calculated theoretically to hit the bar of 70 % according to National Institute for the Industrial Environment and Risks (INERIS) [16]. In this subject, Ramzi et al. [17] proposed a numerical model of a large scale CAES system connected with two adjacent wind farms in Iran composed of two intercooled compressors and preheated turbine. It was shown that the round-trip efficiency of three months (July, August, September) are respectively 52%, 47% and 43%. Wu et al. [18] proposed an innovative hybrid architecture combining cogeneration and AA-CAES based energy hub in a industrial park.

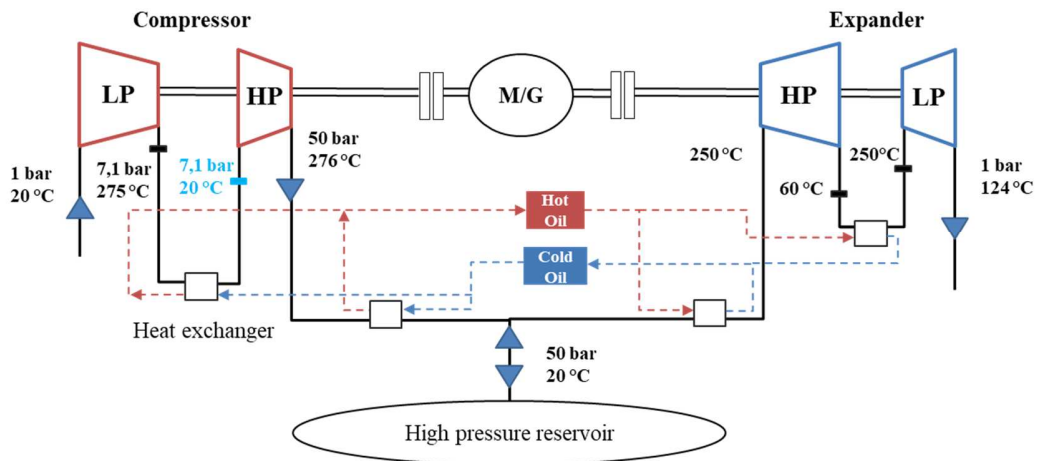


Figure 3: Diagram of an advanced adiabatic CAES system in two-stage configuration [15]

1.3.2. Small scale compressed air energy storage system

Nowadays, many studies are focusing on developing small scale compressed air energy storage systems due to its main advantage which is the connection between a renewable energy module and any energy demand model (building, office, parking, commercial space, housing, hotel,...). These researches target the AA-CAES system with the focus on developing mathematical model based on thermodynamic laws and the heat and cold management in both systems in order to a better comprehension on different system sizing and physical parameters impact (compression/expansion stage number, temperature, pressure, heat transfer,...). In addition, the development of an innovative small volume and high pressure reservoir is currently the main focus for many researchers. In the following section, the studies regarding the trigeneration small scale AA-CAES is investigated from a theoretical and experimental point of view.

Energy and exergy analysis of eight different CAES systems configurations were studied by Kim et al. [15] in order to achieve the highest electrical input/output system efficiency. According to their work, micro AA-CAES system with heat recovery was found to be an effective system for distributed power networks because it can be a combination of energy storage, generation, air-cycle, heating and cooling system and it has a good efficiency (about 60 %). Thermal energy storage (TES) was the main concern of Xue et al. [19] where based on thermodynamic and economic models, they tested hybrid AA-CAES system combining solid and liquid TES. Their hybrid system presented a lower cost for a given efficiency. Li et al. [20] investigated the design of a trigeneration CAES system (T-CAES). With the system design, they found a maximum comprehensive efficiency of a 50 % in winter where no cooling power is needed. Jannelli et al. [21] studied the purpose of polygeneration small-scale compressed air energy storage system integrated with photovoltaic power plant of a radio base station for mobile telecommunications where energy storage strategy and cooling energy production are essential. 57 % of efficiency was noted for their proposed novel trigeneration CAES with a small scale photovoltaic power (3.7 kW compressor constant input power) plant in order to satisfy the electric power demand (1.7 kW expander output power) and to cool the equipment of the radio base station. Li et al. [20] and Jannelli et al. [21] used the same compression/expansion ratio for all the stages. Lv et al. [22] proposed a trigeneration CAES system model working at low pressure (15 bar). They reached 76.3 % of system efficiency noting that their simulated model worked without air preheating before entering the turbine and

supposed that the air charging of the reservoir is an isothermal process. Simpore et al. [23] developed an analytical model based on energy balance and heat transfer equations where they simulated micro AA-CAES system coupled to solar panels and building without heat/cold recovery treatment. Using different energy situation scenarios, the building coverage ratio is higher with the increase of the solar panel area and compressor swept volume. Air tank volume has lower impact in this case.

From an experimental point of view, many small scale pilots for AA-CAES system were proposed recently. Castellani et al. [24] presented a small-scale compressed air energy system prototype connected to a residential photovoltaic plant that ensures the production of 3 kWp. The daily electrical efficiency was noted to be equal to 11.6 % with a compressed air stored at 30 bar in 1.7 m³ vessel. Wang et al. [25] developed a pilot of AA-CAES “TICC-500” with 22.6 % of round trip efficiency which represents the electrical energy output divided by the electrical energy input. Ambient air is compressed via five intercooled compressors (1375 kWh input electric energy; 315 kW for 260 minutes of air compression) and released through a regulating valve that keeps the pressure constant at the inlet of three preheated turbines (326 kWh output electric energy). Cheayb et al. [26] carried out an experimental/numerical approach of a T-CAES composed of three ventilated compression stages driven by 4 kW motor, 300 L air reservoir and air motor coupled to a DC generator of 2 kW. Despite the RTE of 15.6%, a good match between the experimental and numerical model was noticed in their work. Heat removed during compression phase is supposed to answer the heating demand and is not reused to preheat the air entering the turbine [26]. Cold air flow resulted from the expansion process is used to calculate the cooling energy necessary for air conditioning process. In addition to their first study, Cheayb et al. [27] investigated the same trigeneration T-CAES system with the focus on the thermal energy storage giving always the priority to electrical energy production. Two design configurations which depend on the number of heat exchangers and the electric efficiency were proposed. Based on their parametric system optimization study, they showed an improvement of the roundtrip efficiency around 17 % [27]. Borzea et al. developed a first Romanian small scale of compressed air energy installation (ROCAES) with a 100 kW twin-screw compressor and 132 kW screw expander. Compressed air is stored at 26 bar in the vessels whose volume is around 150 m³. They used oil/water heat exchangers for air cooling during compression and for

compressed air preheating before expanding it. A maximum generated power of 49.7 kW was attained with 30 minutes of operation time [28].

2. Work motivation

Based on the French ministry for the ecological transition, the share of tertiary and residential sectors in the final energy consumption is 42 % ahead of the transport sector (30 %), industrial sector (25 %) and agricultural sector (3 %) [29]. The tertiary and residential sectors are responsible for more than 123 million tons of CO₂ emissions making it two of the important key areas in the fight against the global warming and the energy transition. Developing small scale compressed air energy storage (CAES) coupled to building applications is the one of the main pillars of the energy transition subject. Taking the advantage of the work developed for the multiple large scale systems installed worldwide, many researchers are mainly concentrated on developing the hybrid architecture of the small scale CAES system going through each component (compressor, heat exchanger, turbine and high pressure reservoir) in order to increase the inlet/outlet roundtrip electrical or global (electrical, hot and cold) efficiency.

The objective of this study is to derive an optimal design guideline of the small-scale trigenerative advanced adiabatic compressed air energy storage for building application based on thermodynamic and parametric analysis. This article completes a previous study accomplished by Dib et al. [30] where a thermodynamic simulation of a micro advanced adiabatic compressed air energy storage for building application was investigated. The contributions and novelties of the present work as follows:

- The opportunity to simulate a micro compressed air energy storage connected to renewable energy, real building model and energy grids over a one-year period with a time step of one hour.
- The global numerical model is composed by many sub numerical models representing system components and offers the opportunity to vary different compressor/expander or other components parameters without modifying the entire numerical model (renewable energy module, building module, energy grids module and other systems components).
- The global sizing tool offers a wide range of design factor analysis. The studied design factors are: photovoltaic surface, air storage reservoir, heat/cold management,

compressor/turbine stages with variable compression/expansion ratio, compressor/turbine displaced volume and rotation per minute (RPM).

- An optimal micro trigeneration AA-CAES system configuration is proposed. It is coupled to a real building model that is composed of different typologies with specific surfaces and energy consumptions.
- The developed global thermodynamic model focuses in particular on an innovative thermal energy storage module that is connected to the energy storage system and the building model. Therefore, thermal energy storage management is proposed in order to answer building heating and cooling demand.
- The study introduces a two innovative global system operating modes (autonomous and grid connected modes) based on the relationship between the building's energy consumption, the production of renewable energy and the connection to electrical grid which in turn is based on economic benefits.
- The parametric analysis focuses on varying defined energy parameters (10 parameters in total) in function of different geographic scenarios for each operation mode of the system.

3. Methodology and model description

3.1. Global system operation

The global system simulated in this work is composed of four main modules as seen in Figure 4:

- 1) Renewable energy module: solar and wind energy combined to deliver electricity to building model, storage system and electrical grid.
- 2) Building model module: different building typologies with electrical, hot and cold energy demand profiles are proposed in this chapter.
- 3) Energy storage system module: system that stores electrical energy and delivers electrical, hot and cold energy to building and/or electrical grid.
- 4) Electrical and gas grids module: building model is always connected to the electrical and gas grids as an energy backup at all operation modes. In addition, with the “connected mode operation” the energy storage system is connected to the electrical grid for economic advantages.

The global system is modeled based on multiple energy scenarios as follows (Figure 4):

- A. The first priority is to supply the electrical energy building demand using the renewable energy production. (Yellow line A)
- B. If the renewable energy production is higher than the electrical energy building demand then the rest of the green energy is sent to the storage system. (Yellow line B)
- C. Once the storage is saturated, all the excess of the renewable energy production is sent to the electrical grid. (Yellow line C)
- D. If the renewable energy production is lower than the electrical energy building demand then the storage system is called to fill the electrical energy gap. In the same context, the storage system answers building heating and cooling demand. (Yellow, red and blue lines D)
- E. When the global system is in “connected mode operation”, the storage system has the possibility to sell electrical energy to electrical grid after satisfying building electrical load. (Yellow line E)
- F. In any lack of energy response case, electrical and gas grids are considered to answer the rest of energy building demand. Electrical and gas grids are assumed to be connected all the time to the building. (Yellow, red and blue lines F)
- G. In “connected mode operation” the electrical grid is connected to the storage system. When the cost of electricity is cheap (for example: during the night), the electrical grid can provide electrical energy to the storage system in order to store it as a compressed air for high peak of electrical energy consummation. (Dotted dashed yellow line G)

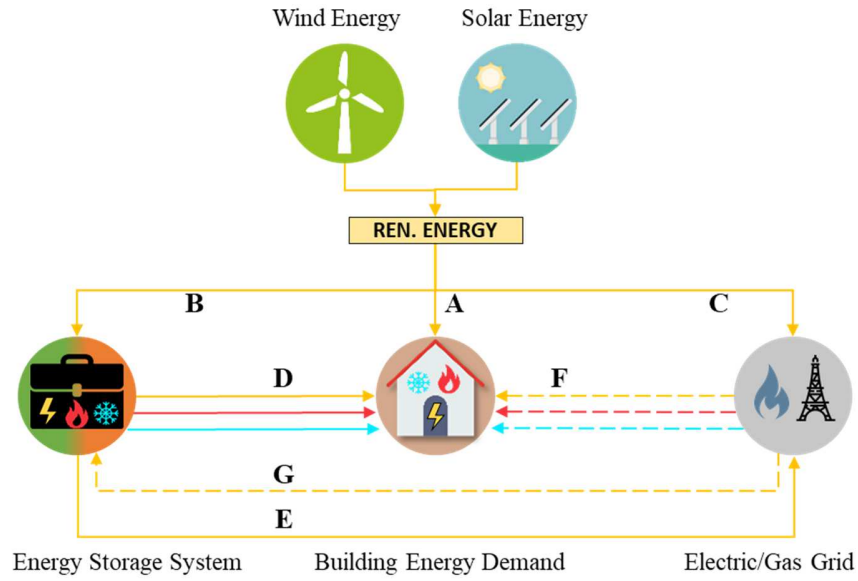


Figure 4: Global system operation (autonomous and connected mode)

In summary, the studied global model focuses on two functional modes:

1. Autonomous mode operation: A + B + C + D + F.
2. Connected mode operation: A + B + C + D + E + F + G.

Four different hourly and monthly energy/grid options are managed in each mode operations:

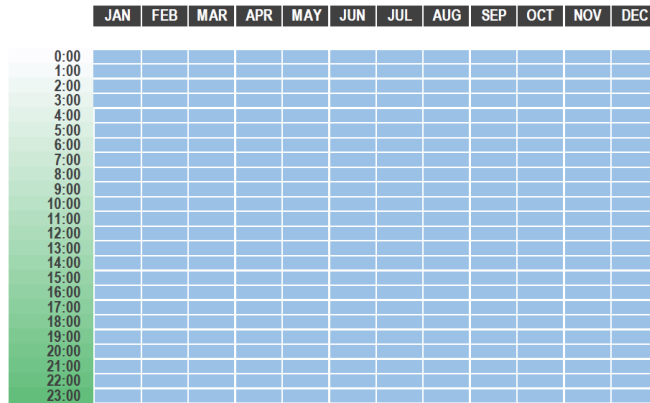


Figure 5: 1st and 2nd global energy management

Renewable energy self-consumption (Line

A): The 1st energy management option is selected all the time during the year.

Answering electrical building demand

from stored electrical energy (Line D): The 2nd energy management option is also programmed all the time of the year.

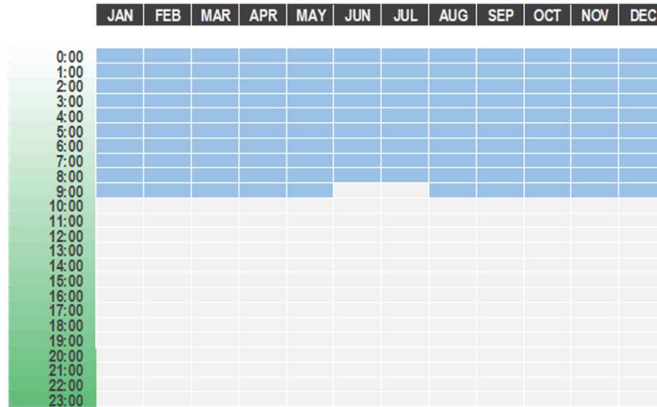


Figure 6: 3rd global energy management

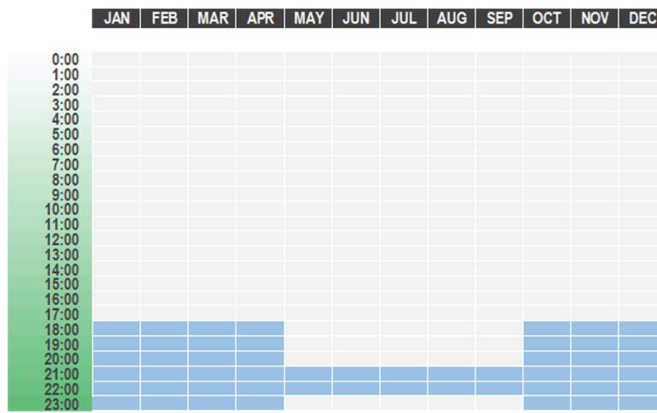


Figure 7: 4th global energy management

Storing energy using the electrical grid –

For connected mode operation (Line G):

The 3rd energy management option is selected during morning hours (0:00 to 9:00) where the electric energy purchase cost is relatively low.

Selling stored electricity to the grid – For

connected mode operation (Line E): The 4th energy management option chosen during the night hours (18:00 to 23:00) for economic benefits.

The mathematical representation of blue and grey cells seen in the global energy management figures (Figure 5-Figure 7) above can be expressed by using the boolean coefficient α that varies with two values: 0 for grey cell and 1 for blue cell.

3.1.1. Micro advanced adiabatic compressed air energy storage system description

The micro AA-CAES system configuration is based on four main elements: Compressor, compressed air reservoir, turbine and hot/cold water reservoir as seen in Figure 8. This system is designed in order to satisfy the energy demand of a building model by storing the excess of renewable energy production. The surplus renewable energy production (solar and wind energy) is used to power the electrical motor that will run the intercooled compressor. During the critical high peak energy building demands, the energy storage system responses by introducing the

compressed air into preheated turbine that turns a generator in order to deliver electrical energy to the user.

The same system configuration example selected in the work done by Dib et al. [30], is taken into consideration in this study as seen in Figure 8 (three compressors and two turbines). Four main phases can be distinguished:

- Charge phase: three intercooled compressors powered by electric motor are used to compress the ambient air to a fixed reservoir pressure (left upper side).
- Storage phase: high pressure reservoir model is considered as constant-volume (middle upper side).
- Discharge phase: compressed air is introduced to a set of heat exchangers and turbines that turn an electrical generator (right upper side).
- Thermal energy unit: multiple heat exchangers are used to cool air at the outlet of the compressor stages and at the same time to preheat the compressed air before entering the turbine stages (left and right middle side). Hot and cold storage are sized based on maximum power daily storage system function: 8 hours for compression phase time and 4 hours for expansion phase time.

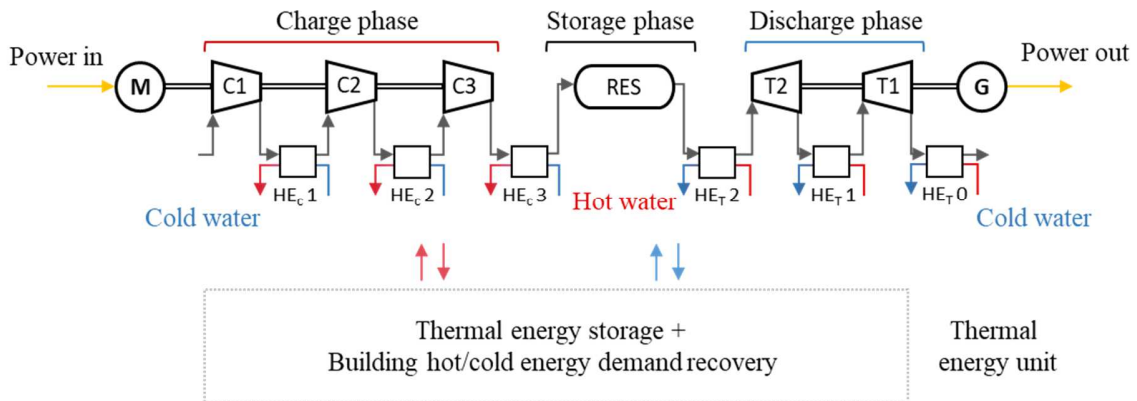


Figure 8: Adiabatic compressed air energy system configuration (for example: 1 reservoir (RES), 3 compressors (C1, C2 and C3), 2 turbines (T1 and T2) and 6 heat exchangers (HE_{c1}, HE_{c2}, HE_{c3}, HE_{t2}, HE_{t1}, and HE_{t0})).

Thermal energy storage is connected to the building model through two heat exchangers in order to answer building heating and cooling demand. Figure 9 shows that the heat recovered from air cooling during compression phase is used to respond building heating demand. In the same manner, cold recovered from compressed air preheating during expansion phase is collected

to answer the building cooling demand. After responding to building heating and cooling demand, hot and cold return water will end up into hot and cold reservoir.

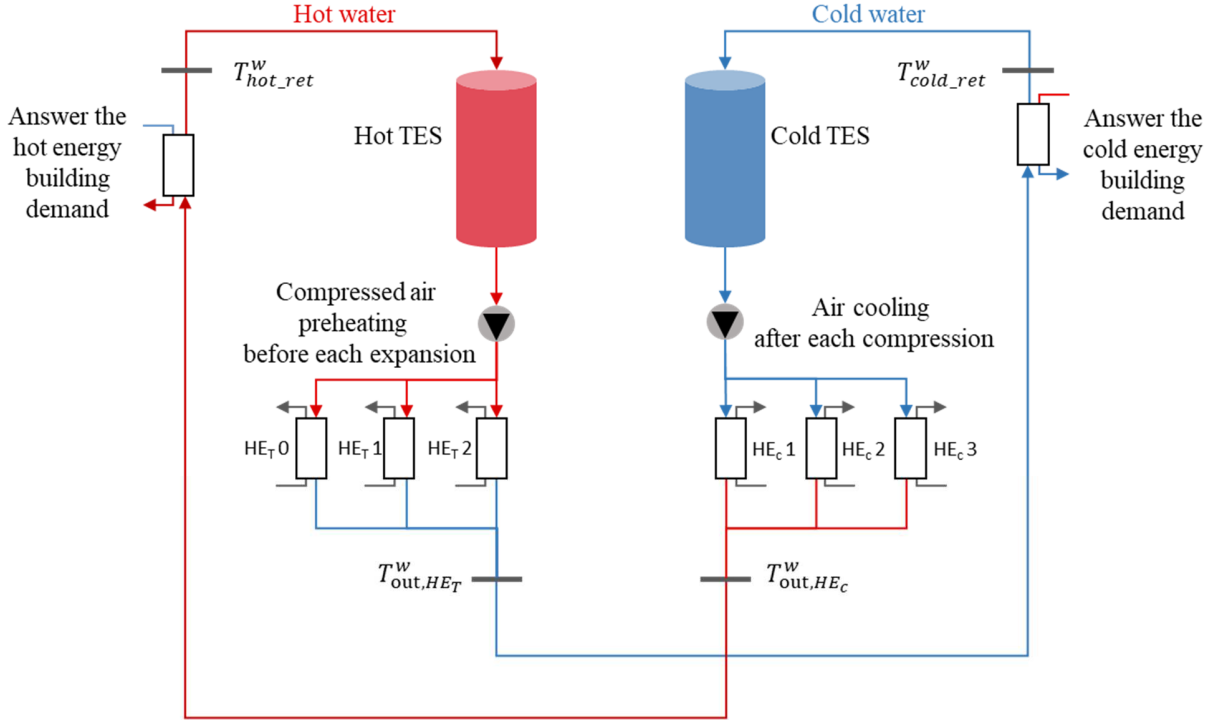


Figure 9: Thermal energy unit configuration for 3 compressors and 2 turbines case

3.1.2. Renewable energy module description

The renewable energy module supplies the building model as a priority and the rest of the renewable production is stored and/or send to the electrical grid. This module is composed of a wind turbines and a photovoltaic panels whose size and surface as well as other parameters related to their production are the global model inputs. The electrical energy produced by the renewable energy module is in the form of direct current and therefore an inverter is needed to convert it to alternating current in order to be injected into the grid [31]. In this study, the renewable energy module is not the main concern, therefore multiple numerical and experimental studies on solar and wind energy are used in order to choose the right renewable energy model inputs [28]. The material of solar panels chosen for the study is monocrystalline and the maximum power output is fixed to 180 W/m². The micro wind turbine chosen for the analysis is described as follow:

- Blade radius: 1.5 m.

- Maximum power output: 25 kW.
- The output power is calculated from multiplying the kinetic energy ($E_k = \frac{1}{2} m V e^2$) and the air mass flow rate passing through the wind turbine ($\dot{m} = V e S \rho$). And therefore, the output power final equation is as follows: $Power = \frac{1}{2} V e^3 S \rho$

3.1.3. Building model description

The building model used in this work was proposed and modeled in AIR4POWER project that is part of the sustainable production and renewable energy program of ADEME's research, development and innovation (RDI) strategy (See appendix). As seen in Figure 10, the building model is composed of different typologies with a total surface of 6813 m².

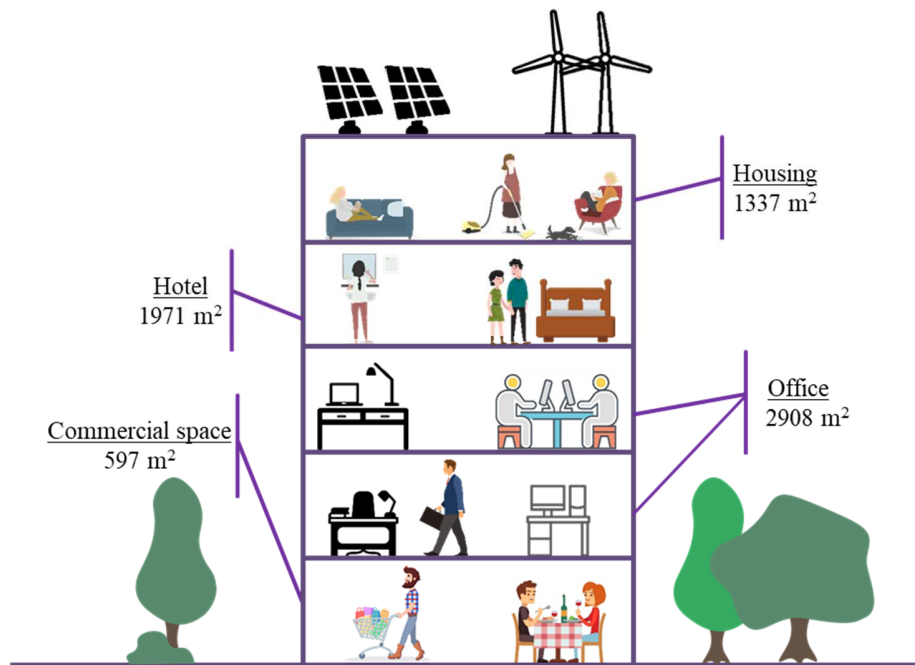


Figure 10: Building model typologies considered for this work

3.2. Thermodynamic analysis

3.2.1. Model assumption

- Air is considered as ideal gas.
- Potential and kinetic energy are negligible.

High pressure reservoir

- Steel reservoir is considered in this case.

- Maximum and minimum reservoir pressure are fixed (P_{max}, P_{min}).
- High pressure reservoir is considered as constant volume.
- The product of reservoir global thermal coefficient and its surface ($(KS)_{res}$) is assumed to be known to 125 W/K (inspired by Simapore's work) [32]

Compressor/expander technology

- Cylinder piston volumetric compressor/turbine are considered in this system.
- Displacement volume for the first stage of compressor and turbine are fixed.
- Compressors and turbines are mounted on the same crankshaft separately.

Thermal energy storage

- The efficiencies (ε) of heat exchangers ($\varepsilon = \frac{q}{q_{max}}$) are fixed to 90 %.
- After each air compression, hot water exits the heat exchanger at 70 °C (T_{out,HE_c}^w).
- After each air expansion, cold water exits the heat exchanger at 5 °C (T_{out,HE_t}^w).
- Hot water return temperature ($T_{ho_ret}^w$) is fixed at minimum 40 °C.
- Cold water return temperature ($T_{co_ret}^w$) is fixed at maximum 15 °C.
- Hot and cold water reservoirs are considered to be adiabatic.

3.2.2. Analytical model of the energy storage system module

The analytical models of the components (compressor, turbine, heat exchanger) used in this global model are quite the same models developed in Dib et al. work [30]. In the following section, the new and modified components are detailed. The different system scenarios discussed in section “3.1. Global system operation” are chosen based on the energy difference (ΔE) between the hourly renewable energy production and electrical energy building demand in addition to the possibility of buying from and selling to electrical grid as described in Eq. (1). ΔE imposes the input air mass flow to the compressor stages (\dot{m}_c) showed in Eq. (2) which is function of the total compressor work ($\sum_{i=1}^{N_c} w_{c,i}$) and in other words function of the working reservoir pressure.

$$\Delta E = (E_{PV}(t) + E_W(t)) - E_{EBD}(t) + (\alpha E(t))_{GR-ST} + (\alpha E(t))_{ST-GR} \quad (1)$$

$$\dot{m}_c = \frac{\Delta E}{\sum_{i=1}^{N_c} w_{c,i} \Delta t} \quad (2)$$

$$\dot{m}_c = \frac{(E_{PV}(t) + E_w(t)) - E_{EBD}(t) + (\alpha E(t))_{GR-ST} + (\alpha E(t))_{ST-GR}}{\sum_{i=1}^{N_c} w_{c,i} \Delta t} \quad (3)$$

The high pressure reservoir model is considered to be constant-volume ($w = 0$). The reservoir model used in this study is based on the investigations carried out by Simporé [32] who developed an analytical reservoir model that takes into consideration the heat loss/gain to/from the surroundings. The energy balance equation for the air entering the air reservoir is as follows:

$$d(mu) = +\dot{m}_c h_{in} dt + \delta Q = h_{in} dm + \delta Q \quad (4)$$

Substituting the enthalpy and internal energy formulas into Eq. (4), results in the following ordinary differential equation:

$$\frac{dT}{dt} = \frac{(\gamma T_{in,res} - T_{res})}{m} \frac{dm}{dt} + \frac{(KS)_{res}}{mc_v} (T_{amb} - T_{res}) \quad (5)$$

With K the global heat transfer coefficient. From this latter equation, the reservoir temperature is calculated as a function of the air mass flow (\dot{m}_c) entering the reservoir and its temperature ($T_{in,res} = T_{out,HEC,i}$). By integrating Eq. (5) between j and $j+1$ time step, the numerical air reservoir temperature at $j+1$ time step can be expressed by the following:

$$(T_{res})_{j+1} = \left[\frac{(\gamma T_{in,res} - T_{res})_j}{m_j + \dot{m}_c \Delta t} \dot{m}_c + \frac{(KS)_{res}}{(m_j + \dot{m}_c \Delta t) c_v} (T_{amb} - T_{res})_j \right] \Delta t + (T_{res})_j \quad (6)$$

The ideal gas equation is used to calculate the increase of reservoir pressure at each time step (j) or the pressure decrease for air releasing phase. In the same way, as for the air entering phase, the energy conservation equation for the air leaving the high pressure reservoir is described by Eqs.(5-6) :

$$d(mu) = -\dot{m}_t h_{out} dt + \delta Q = +h_{out} dm + \delta Q \quad (7)$$

In this case, $T_{out,res} = T_{res}$ and Eq. (7) can be simplified to:

$$\frac{dT}{dt} = \frac{(\gamma T_{out,res} - T_{res})}{m} \frac{dm}{dt} + \frac{(KS)_{res}}{mc_v} (T_{amb} - T_{res}) \quad (8)$$

Equation (8) which is an ordinary differential equation can be solved numerically by calculating the air reservoir temperature at $j+1$ time step after releasing air mass m_{j+1} as follows:

$$(T_{res})_{j+1} = \left[\frac{(\gamma T_{res} - T_{res})_j}{m_j + \dot{m}_t \Delta t} \dot{m}_t + \frac{KS_{res}}{(m_j + \dot{m}_t \Delta t)c_v} (T_{amb} - T_{res})_j \right] \Delta t + (T_{res})_j \quad (9)$$

When electrical discharging phase is applied in both scenarios (D) and (E), the output air mass flow from storage reservoir entering the turbine stages is calculated as follow:

$$\dot{m}_t = \frac{\Delta E}{\sum_{i=1}^{Nt} w_{t,i} \Delta t} \quad (10)$$

$$\dot{m}_t = \frac{(E_{PV}(t) + E_w(t)) - E_{EBD}(t) + (\alpha E(t))_{GR-ST} + (\alpha E(t))_{ST-GR}}{\sum_{i=1}^{Nt} w_{t,i} \Delta t} \quad (11)$$

Polytropic process is considered in order to calculate compression ($w_{c,i}$)/expansion ($w_{t,i}$) work and compressor/turbine output temperature.

The following section focuses on the behavior of the thermal energy storage during the charge phase. Based on the heat transfer equation, the cold water mass flow rate needed to cool compressed air is calculated as follow:

$$\dot{m}_{out,co,i}^w = \frac{\dot{m}_c c_p (T_{in,HE_c,i} - T_{out,HE_c,i})}{c_p^w (T_{out,HE_c,i}^w - T_{in,HE_c,i}^w)} \quad (12)$$

Where $T_{out,HE_c,i}^w = 70$ °C and $T_{in,HE_c,i}^w = T_{co_ST}^w(j)$. It should be noted that this water mass flow rate will end up by entering the hot water storage. After cold water storage response, the temperature of that storage $T_{co_ST}^w(j)$ is assumed to remain constant. Therefore, the cold water storage mass is calculated with Eq.(13):

$$dm_{co_ST} = -\dot{m}_{co,i}^w dt \quad (13)$$

In turn, hot water recovered during the air cooling process answers the building heating demand. This hot energy answer is limited by a minimum hot return temperature ($T_{ho_ret}^w$) that is equal to 40 °C. The mass and temperature of hot water storage are then calculated as following:

$$dm_{ho_ST} = +\dot{m}_{co}^w dt = +\dot{m}_{ho}^w dt \quad (14)$$

$$\frac{dT_{ho_ST}^w}{(T_{out,HE,i}^w - T_{ho_ST}^w)} = \frac{dm}{m} \quad (15)$$

The previous equation Eq. (15) can be solved numerically as follows:

$$T_{ho_ST}^w(j+1) = \left(T_{ho_ST}^w(j) \frac{m_{ho_ST}(j)}{m_{ho_ST}(j+1)} \right) + (T_{ho_ret}^w (1 - \frac{m_{ho_ST}(j)}{m_{ho_ST}(j+1)})) \quad (16)$$

The equations below regard the thermal energy storage during the discharge phase. Similar to the charge phase, hot water mass flow rate needed to preheat the compressed air before expanding it is described in the following:

$$\dot{m}_{out,ho,i}^w = \frac{\dot{m}_t c_p (T_{out,HE,i} - T_{in,HE,i})}{c_p^w (T_{out,HE,i}^w - T_{in,HE,i}^w)} \quad (17)$$

Where $T_{out,HE,i}^w = 5^\circ\text{C}$ and $T_{in,HE,i}^w = T_{ho_ST}^w(j)$. It should be mentioned that the hot water mass flow rate will end up by entering the cold water storage. After hot water storage response, the temperature of that storage $T_{ho_ST}^w(j)$ is assumed to remain constant. Therefore, the hot water storage mass is calculated with Eq. (18):

$$dm_{ho_ST} = -\dot{m}_{ho,i}^w dt \quad (18)$$

In turn, cold water recovered during the air preheating process answers the building cooling demand. This cold energy answer is limited by a maximum cold return temperature ($T_{co_ret}^w$) that is equal to 15°C . The mass and temperature of cold water storage are then calculated as follows:

$$dm_{co_ST} = +\dot{m}_{ho,i}^w dt = +\dot{m}_{co}^w dt \quad (19)$$

$$\frac{dT_{co_ST}^w}{(T_{out,HE,i}^w - T_{co_ST}^w)} = \frac{dm}{m} \quad (20)$$

The previous equation Eq. (20) can be solved numerically as follows:

$$T_{co_ST}^w(j+1) = \left(T_{co_ST}^w(j) \frac{m_{co_ST}(j)}{m_{co_ST}(j+1)} \right) + (T_{co_ret}^w (1 - \frac{m_{co_ST}(j)}{m_{co_ST}(j+1)})) \quad (21)$$

4. Numerical analysis of the global system

The iterative approach used in this numerical global model to solve these equations detailed above are represented in the flowchart of Figure 11. Four inputs modules (wind turbine/solar production, energy building demand and system parameters) are called at each hourly time step (j) for each single day (a) of the year. The data collected is analyzed and then based on energy condition (ΔE), the energy scenario discussed in section 2.1 is chosen. Therefore, within the same time step (j), the electrical loop that deals with electrical energy coming/going from/to different energy resource/user is analyzed at first place. And then comes the investigation of the thermal unit module. The global model is coded using EXCEL VBA program. Different main and sub modules of the numerical tool used to dynamically calculate and analyze the performance of the global system.

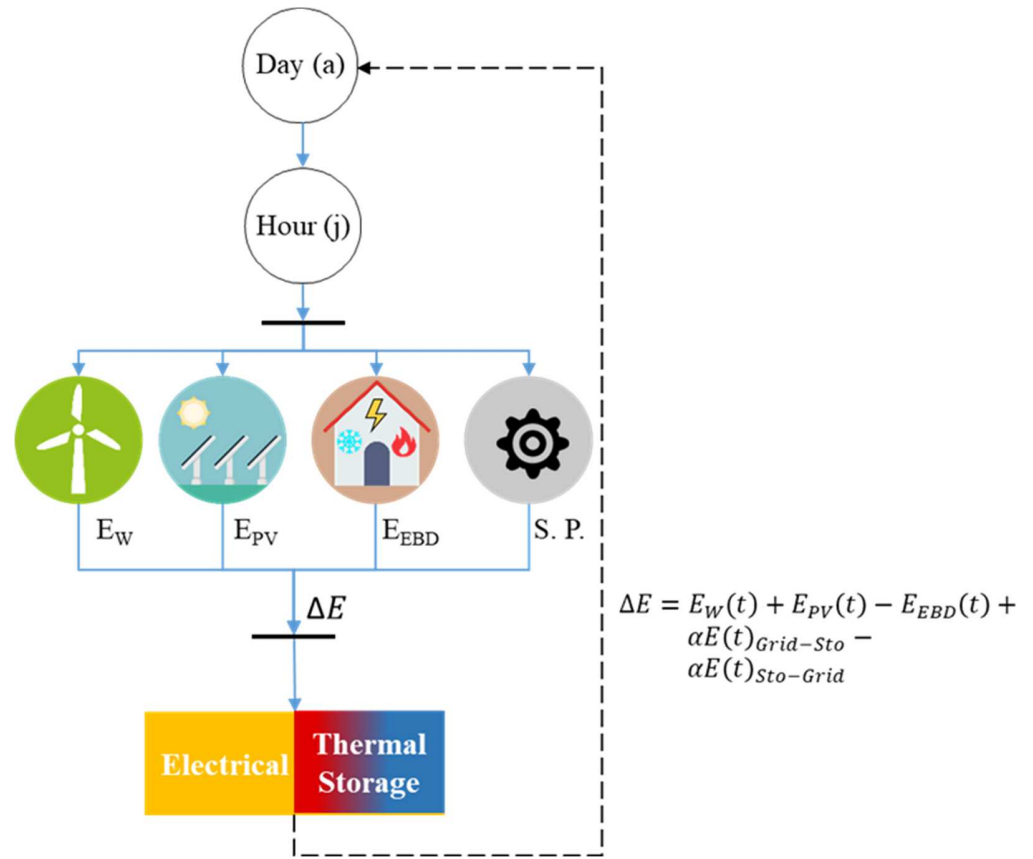


Figure 11: Global numerical code of the micro AA-CAES flow chart

5. Results and discussions

The global system simulated in the next section, is composed of three compressors and two turbines. In order to study the two operation modes (autonomous and connected), "Nice" the French city is chosen as a geographical scenario. Other inputs and constraints required for the sizing procedure are listed in the following tables:

- Table 1: related to compressed air energy storage system and to renewable energy module (solar panels and wind turbine).
- Table 2: related to thermal energy module (thermal storage and heat exchanger).

Table 1: Input data and constraints related to CAES and R.E. unit

CAES unit		R.E. unit	
Air reservoir volume	35 m ³	<u>Solar panel</u>	
Initial reservoir temperature	20 °C	Surface	1000 m ²
Max. air reservoir pressure	200 bar	Efficiency	20 %
Min. air reservoir pressure	10 bar	Maximum	180 W/m ²
Max. power input/output	100 kW	power output	
Number of compression stages	3	Material	Monocrystalline
Compression ratios ($\beta_{c,1}, \beta_{c,2}, \beta_{c,3}$)	10, 5, 4	<u>Wind turbine</u>	
1 st compressor displacement volume	0.0006 m ³	Blade diameter	1.5 m
Number of expansion stages	2	Maximum	25 kW
Expansion ratios ($\beta_{t,1}, \beta_{t,2}$)	5, 10	power output	
1 st turbine displacement volume	0.0006 m ³		
Polytropic index	1.4		
Polytropic efficiency	80 %		

Table 2: Input data and constraints related to thermal energy unit

Thermal energy unit			
<u>Thermal Storage</u>		<u>Heat exchangers</u>	
Initial cold water temp	20 °C	Efficiency	90 %
Cold storage volume	8 m ³	Outlet temperature	70 °C
Initial hot water temp	20 °C	(compressor)	
Hot storage volume	8 m ³	Outlet temperature	5 °C

Minimum input temperature 40 °C (*turbine*)
(*hot storage*)
Maximum input temperature 15 °C
(*cold storage*)

Monthly renewable energy production (R.E.) and electrical building demand (E.B.D.) are shown in Figure 12. Similarly, the hot/cold energy building demand are presented in Figure 13 and Figure 14 respectively.

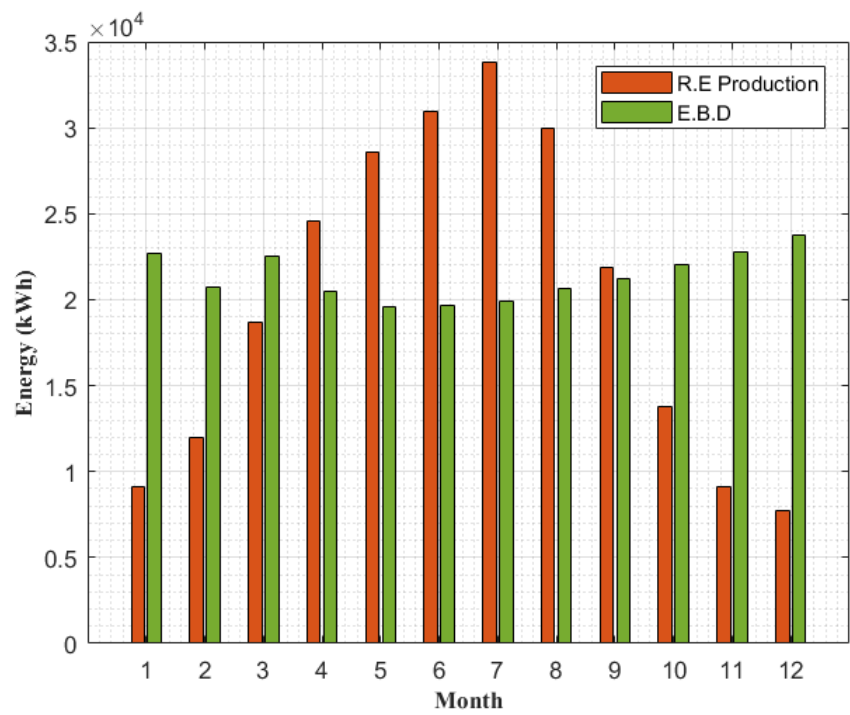


Figure 12: Monthly renewable energy production (R.E.) and electrical building demand (E.B.D.) for Nice location

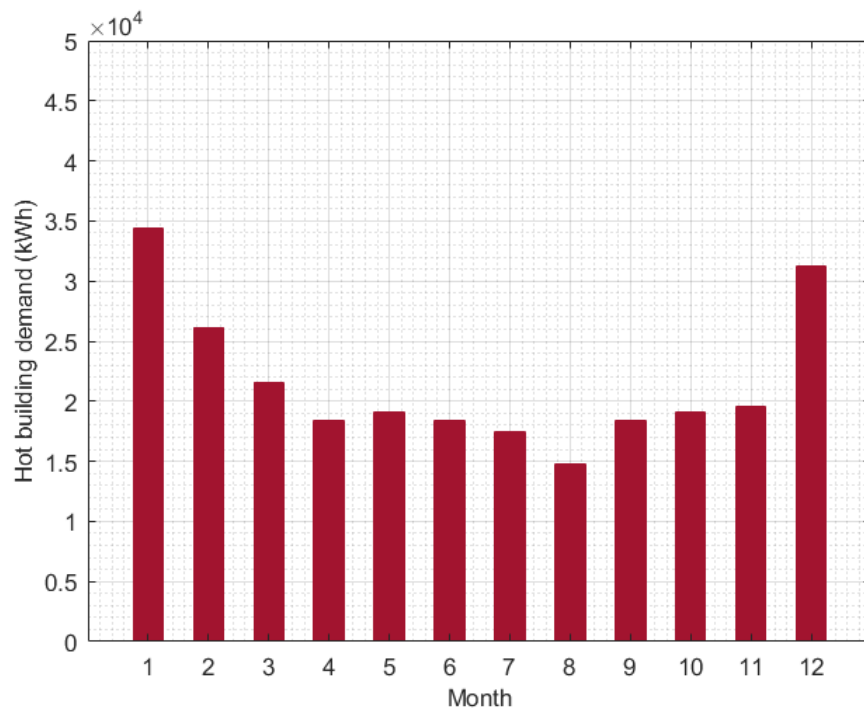


Figure 13: Monthly hot energy building demand (H.B.D.) for Nice location

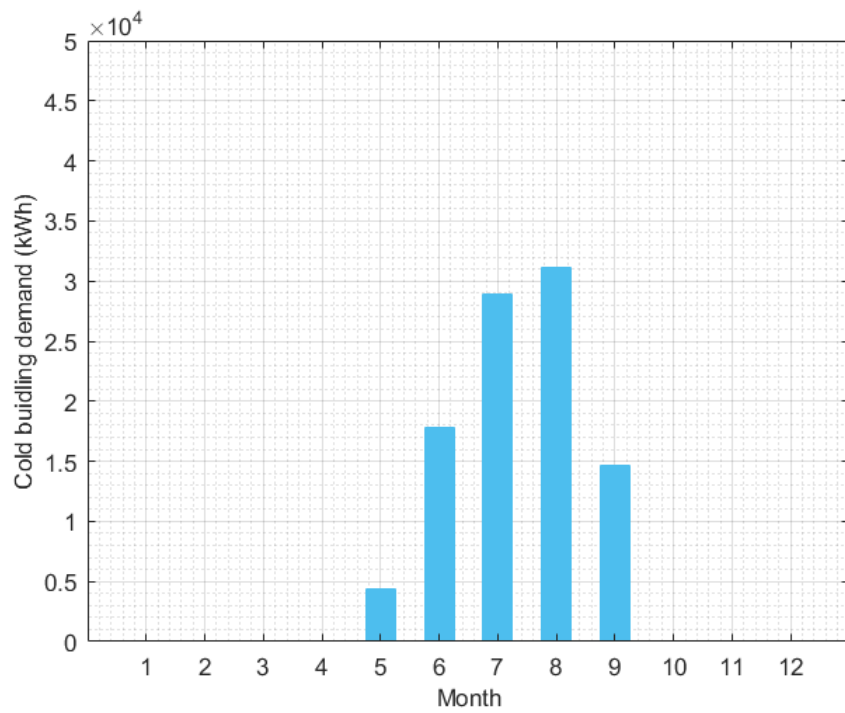


Figure 14: Monthly cold energy building demand (C.B.D.) for Nice location

5.1. Autonomous mode operation

For the purpose of satisfying the energy building demand (electrical, hot and cold) based on renewable energy production (solar and wind), the autonomous mode operation is selected. In this case of mode operation, the two energy grids (electrical and gas) are just on standby in case renewable energy production is not sufficient. By applying the proposed numerical methodology, four different energy sources can be represented in Figure 15. The same behavior is noticed for the energies derived directly from the renewable energy production (R.E. self-production) and from the AA-CAES system (Energy from storage) all over the year. Summer days (May, June, July and August) show clearly this fact where energy derived from the storage scores the highest values (in July around 4 833 kWh). It is worth mentioning that in some cases (for example: July) the electrical energy building demand is totally answered and the rest of renewable energy production is sent to the electrical grid (4 000 kWh in July).

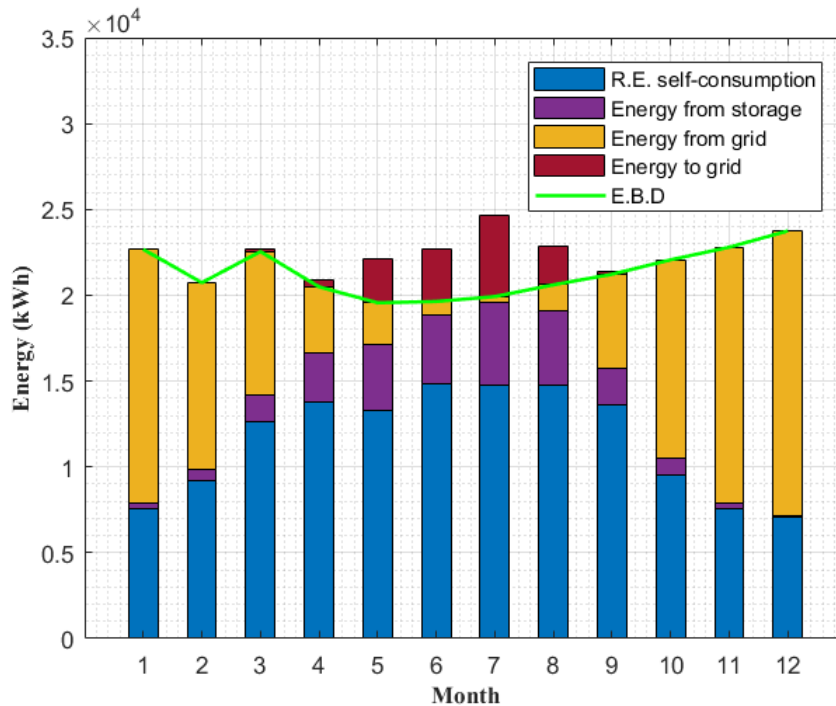


Figure 15: Different sources of electrical energy responding to electrical energy building demand (autonomous mode operation)

Figure 16 and Figure 17 show the hot/cold building demand answered by hot/cold water storage and an alternative energy. As discussed in section 2.1.1, the hot water recovered after cooling the air during compression phase responds to building heating demand. Based on Figure 12, the renewable energy production increases from May to July and then begins to decrease till November. This R.E. production behavior affects directly the air compression operation and consequently the hot water respond (Figure 16). It should be mentioned that the hot and cold water storage are sized (8 m^3) based on daily AA-CAES operation: 8 hours of air compression at maximum power (100 kW) and 4 hours of air expansion at the same power. Building heating demand answered by the thermal unit is around 8 % per the year. As can be seen in Figure 17, building cooling demand answered by the thermal energy unit is considered low (4 %). This is justified in some cases where the air reservoir temperature is higher than the hot water storage temperature. This fact has two important contradictory consequences:

- An important air reservoir temperature insures a better air expansion and therefore a better AA-CAES electrical output power.
- Compressed air is not preheated before expansion and therefore no building heating demand respond.

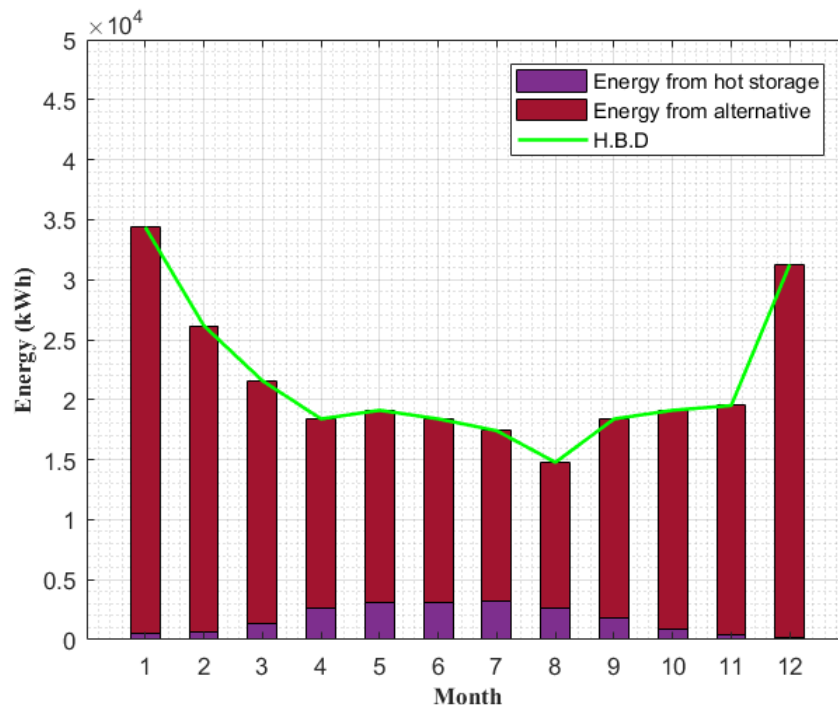


Figure 16: Monthly building heating demand answered by hot water storage and non R.E. source (autonomous mode operation)

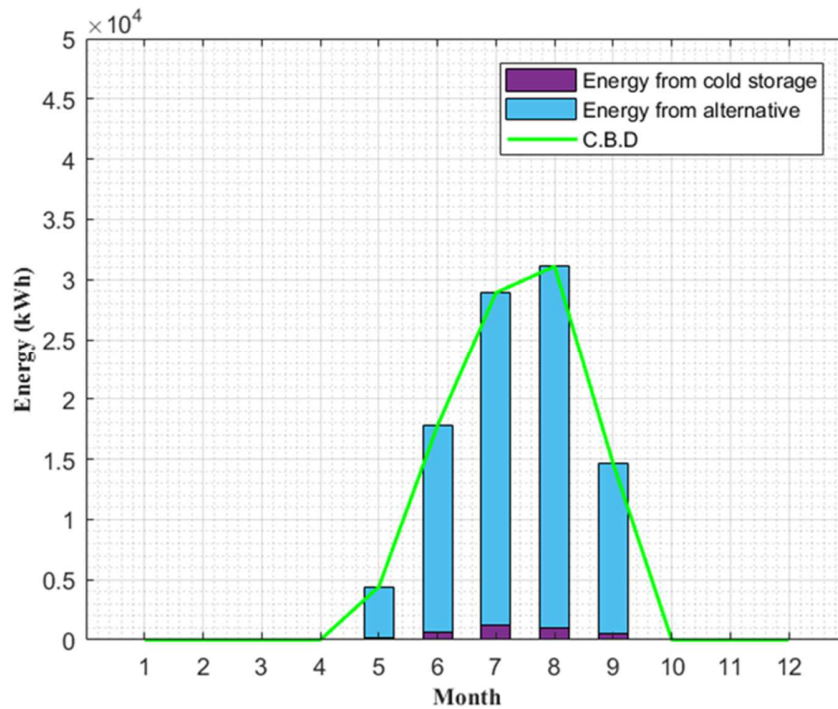


Figure 17: Monthly building cooling demand answered by cold water storage and non R.E. source (autonomous mode operation)

5.2. Connected mode operation

The connected mode operation takes the economic advantage where the system can store/sell electricity coming from/to the electrical grid in addition to the storing of renewable energy, in order to answer the energy building demand. Four different hourly and monthly energy/grid options are managed in this mode operation:

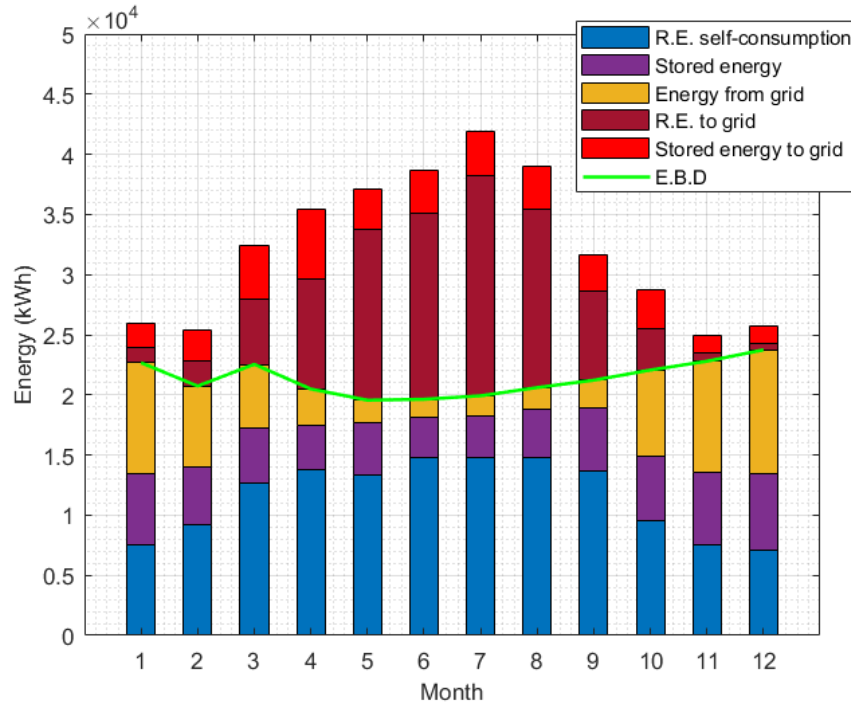


Figure 18: Different sources of electrical energy responding to electrical energy building demand (connected mode operation)

Unlike the autonomous mode operation, Figure 18 shows that the share of energy answered by the storage system is more important. An important part of renewable energy (R.E.) is sent to the electrical grid due to the storage saturation based on storing energy from the grid during morning hours. In the connected mode operation, the high pressure reservoir achieves rapidly the maximum pressure (200 bar) and thus the storage system has a tendency to deliver more energy to the building and to the electrical grid.

It should be noted that in Figure 19 and Figure 20 the building heating and cooling demand answered by the thermal energy unit is more favorite in the connected mode operation. 20 % of the building heating demand covered by the hot water storage whereas 5 % for cold energy. Cold part remains relatively low because of the high temperature (around 100 °C) stored in high pressure reservoir. This fact promotes higher electrical output power but on the other hand reduces the cold water recovered from preheated turbines and therefore less cold energy building response.

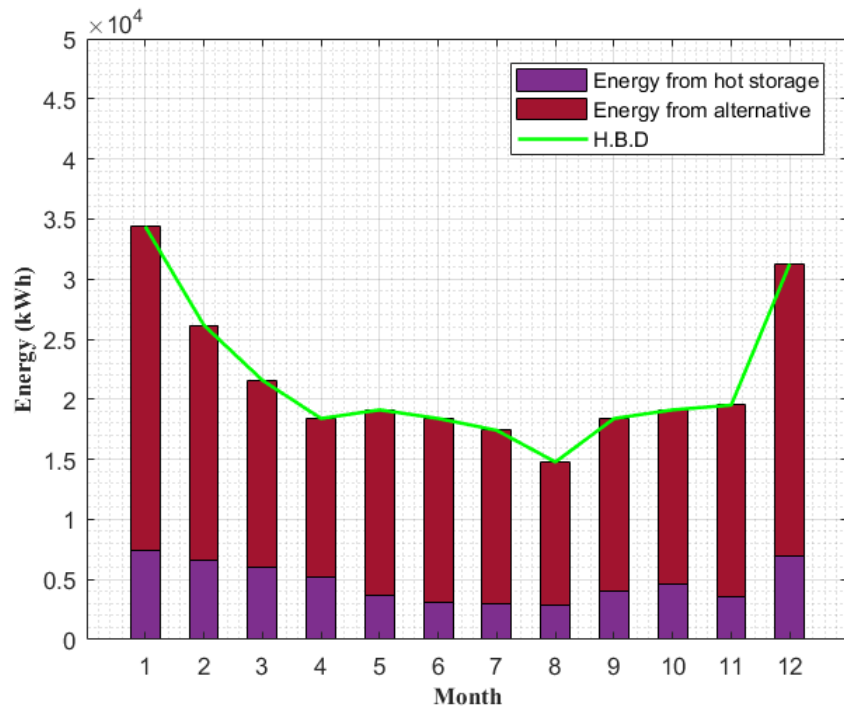


Figure 19: Monthly building heating demand answered by hot water storage and non R.E. source (connected mode operation)

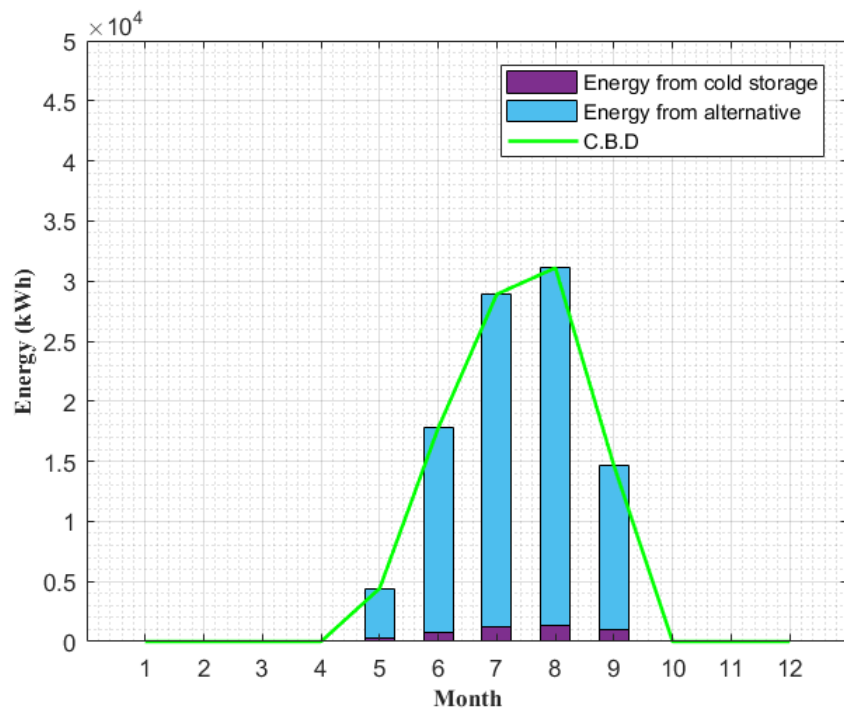


Figure 20: Monthly building cooling demand answered by cold water storage and non R.E. source (connected mode operation)

5.3. Parametric analysis

In this section, the different energy scenarios discussed in 2.1 are analyzed using four main indicators (electrical, hot, cold and trigeneration energy) as seen in Table 3.

Table 3: Four indicators regrouping different analysis parameters each

Electrical energy			
E.C.R.	Electrical coverage ratio	$E.C.R. = \frac{W_t}{\text{Electrical total consumption}}$	(22)
E.S.E.	Electrical system efficiency	$E.S.E. = \frac{W_t}{W_c}$	(23)
E.L.M.	Electrical load management	$E.L.M. = \frac{\text{Min}(R.E., E.B.D.) + W_t}{\text{Electrical total consumption}}$	(24)
Hot energy			
H.C.R.	Hot coverage ratio	$H.C.R. = \frac{\text{Energy from hot water storage}}{\text{Building heating energy demand}}$	(25)
H.R.	Hot recovered	$H.R. = \frac{\text{Energy from hot water storage}}{W_c}$	(26)
Cold energy			
C.C.R.	Cold coverage ratio	$C.C.R. = \frac{\text{Energy from cold water storage}}{\text{Building cold energy demand}}$	(27)
C.R.	Cold recovered	$C.R. = \frac{\text{Energy from cold water storage}}{W_t}$	(28)
Trigeneration			
T.C.R.	Total coverage ratio	$T.C.R. = \frac{W_t + \text{Energy from (hot + cold) water storage}}{(\text{Electrical} + \text{Hot} + \text{Cold}) \text{ total consumption}}$	(29)
T.S.E.	Trigeneration system efficiency	$T.S.E. = \frac{E_{ST-B} + \text{Energy from (hot + cold) water storage}}{W_c}$	(30)
E.T.S.E.	Exergy trigeneration CAES system efficiency	$E.T.S.E. = \frac{ E_{ST-BD} + \theta_{ho} Q_{ho} + \theta_{co} Q_{co} }{W_c}$	(31)

Three different geographical locations of France (Strasbourg, Nantes and Nice) are chosen to be studied in the following in order to have a global view related to the micro AA-CAES behavior.

Table 4 and Table 5 list the different parameters detailed above for autonomous and connected mode operation where the input data is taken as the optimal condition parameter for the proposed system.

Table 4: Parametric analysis results (Autonomous mode operation)

	Strasbourg	Nantes	Nice
E.C.R.	6.04 %	7.52 %	9.74 %
E.S.E.	25.71 %	27.21 %	28.22 %
E.L.M.	50 %	54 %	63.9 %
H.C.R	3.24 %	5.03 %	7.56 %
H.R.	22.64 %	23.72 %	22 %
C.C.R.	4 %	6 %	4 %
C.R.	10.06 %	8.02 %	14.59 %
T.C.R.	4.28 %	6.32 %	7.87 %
T.S.E.	50.92 %	53.08 %	54.37 %
E.T.S.E	29.15 %	30.79 %	31.66 %

Table 5: Parametric analysis results (Connected mode operation)

	Strasbourg	Nantes	Nice
E.C.R.	25.52 %	24.75 %	21.8 %
E.S.E.	42.08 %	34.29 %	34.61 %
E.L.M.	69.5 %	71.2 %	75.9 %
H.C.R	12.23 %	17.43 %	19.92 %
H.R.	22.93 %	21.69 %	19.41 %
C.C.R.	5 %	8 %	5 %
C.R.	2 %	2.55 %	5.55 %
T.C.R.	16.42 %	20.05 %	18.39 %
T.S.E.	52.41 %	46.16 %	42.37 %
E.T.S.E	45.44 %	37.49 %	37.54 %

In best energetic case configuration, micro AA-CAES system in the connected mode operation presents more advantages than the autonomous mode operation. This result is justified by the fact

that the storage system is connected to the electrical grid meaning more air compression/expansion cycles. However, the electrical coverage ratio (E.C.R.) remains low in both modes (9.74 % and 21.8 %). This latter coverage ratio shows a fair agreement with the one resulted numerically by Simpure [32]. More air compression cycles led to an increase in the heat coverage ratio with the connected operation mode while the important air reservoir temperature limits the cold coverage ratio in both modes of operation. Heat recovered (H.R.) and cold recovered (C.R.) show to be important in autonomous mode operation. The latter fact is due to the important increase of the total compression work (W_c) and total expansion work (W_t) compared to the increase of the hot/cold energy from hot/cold storage while switching from autonomous to connected mode operation.

6. Conclusion and perspectives

An optimal numerical micro AA-CAES model is presented in order to satisfy building electrical, heating and cooling demand taking into consideration different energy scenarios. The research is focused on studying different design parameters based on a global numerical sizing tool which in turn based on solving energy balance and heat transfer equations for each system components. In order to have the best compromise between the electrical energy and building heating/cooling responses, an innovative mathematical thermal energy storage module is proposed in this paper.

Two modes of operation are proposed in this study:

1. Autonomous mode operation : The energy storage system is connected to the building, to the renewable energy module and to electrical/gas grid (for any lack of energy response)
2. Connected mode operation: This mode has one particularity in addition the previous mode operation which is the possibility for the energy storage system to sell/buy electrical energy from/to electrical grid (in profitable conditions)

The numerical methodology proposed in this article is based on iterative approach that has allowed to size each component of the global energy storage system and to calculate their operating conditions and performance. The numerical results have highlighted the following:

- Connected mode operation scores more advantages points than the autonomous mode operation in most of the energy and geographical scenarios. An increase of 12.06 %, 12.34 % for the electrical coverage ratio and for the hot coverage ratio respectively taking

Nice as a geographical location while switching from autonomous to connected mode operation.

- The cold coverage ratio remains relatively poor in both mode operations. The best electrical system efficiency was equal to 42 % in Strasbourg case for connected mode operation.
- The thermal storage response is related to the compression/expansion cycles frequency and to the electrical system efficiency.
- The trigeneration system efficiency is a compromise between electrical system efficiency, hot coverage ratio and cold coverage ratio. In Strasbourg location, the trigeneration system efficiency scores 52.41 %.

Future work will highlight on the levelized cost of energy (LCOE) analysis accomplished for the micro AA-CAES in the connected mode operation especially that it was noticed from this paper that this mode presents more global economic advantages. Electrical vehicle, compressed air vehicle, compressed air bikes and other concepts linked to the energy storage system should be investigated. In addition, it would be interesting to take into consideration the ambient temperature variation throughout the year depending on the location where the AA-CAES system is installed. Furthermore, the analytical models developed in this article were used in Dib's thesis work, where a global numerical sizing tool was elaborated to simulate a small-scale compressed air energy storage system [33].

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Appendix: AIR4POWER Project

AIR4POWER project developed by AIA LIFE DESIGNERS is based on an adiabatic compressed air system (A-CAES - Adiabatic Compressed Air Energy Storage) allowing energy to be stored in order to restore it in four different energy types (electricity, heat, cold and compressed air) with a relatively important global energy efficiency. An interconnection of buildings with thermal and electrical networks (smartgrid type) is also proposed in this project in order to increase and optimize the renewable energy integration into the final energy consumption. Five applications are currently being considered:

- Urban energy storage module (smart-grid).
- Energy storage integrated into spaces and fallow volumes or undergoing conversion.
- Energy consumption peaks removal and electricity resale from industrial sites.
- Buildings with integrated energy storage (use of opportunistic voids in structures).
- Energy storage for non-interconnected areas (ZNI) (islands, mountains, nature reserves).

AIR4POWER project was integrated in many research projects like ADEME's research project where a building model was modeled and calibrated. In order to calculate the energy building needs, a dynamic thermal simulation is achieved during the AIR4POWER project over one meteorological year. Multiple hypotheses were assumed related to wall characteristics, glazing, and lighting. For instance, real occupancy profiles were used where heat generated from one person is estimated to 115W/occupant: 70 W sensible heat and 45 W latent heat. The assumed occupancy according to different typologies are as follows:

- Commercial space : 5 m²/person ;
- Office : 2 occupants per office ;
- Open-spaces : 7 m²/person ;
- Meeting rooms : 4 m²/person ;
- Hall and circulations : 1 person for 25 m² ;
- Housing, depends on the type
 - o Type 1 hotel room = 1 person ;
 - o Type 2 = 2 people ;
 - o Type 3 = 3 people ;
 - o Type 4 = 4 people.

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